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Control strategy for an Internal Combustion engine fuelled by Natural Gas operating in Distributed Generation

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Abstract

The paper presents a control strategy concept for an Internal Combustion (IC) engine to work in Distributed Generation. The control strategy is based on several factors and directs the operation of the IC engine in the context of changes occurring in the market, while taking into account the operating characteristics of the engine. The control strategy is defined by an appropriate objective function: for example, work at maximum profit, maximum service life, etc. The results of simulations of a piston engine at chosen loads are presented. Daily changes in the prices of fuel and electricity are factored into the simulations.

Keywords: Distributed Generation; control strategy; piston engine; internal combustion engine; Natural Gas

1. Introduction

Rising fuel prices combined with an upward trend in electricity consumption are providing strong incentives for research into systems that boost generation efficiency.

Decentralized systems are beginning to prevail over centralized models. Very eloquent examples, schematically, are provided by mobile phone networks and the Internet. It is expected that Distribution Generation [1] consisting of many small units will dominate in the near future. In this system, electricity will be produced by small sources installed directly alongside consumers of energy and working mainly to meet their needs [2]. These sources must meet specific requirements including: high generating efficiency, providing most of the energy needs of a facility and possibly providing a small amount of delivered fluids (such as fuel only).

An electricity distribution system based on a network of small, interconnected sources is characterized by both load variability and changing electricity prices. This means that the sources will have to adapt to the load not only for local changes, but also as it relates to the market balance between buyers and sellers of power to the grid and changes in fuels markets.

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The DG system has many advantages, including very high certainty of supply, high efficiency power generation (both electricity and cogeneration) and high adaptability to changes in demand (both daily and annual). The DG system can be compared in its essence and mode of operation to the Internet or to mobile networks.

Distributed generation and renewable energy sources in Europe and worldwide [3] have attracted considerable interest and are viewed as essential in the light of two political objectives:

- increasing Europe's energy security by reducing dependence on imported fossil fuels such as petroleum, natural gas and coal,
- reducing greenhouse gas emissions, especially carbon dioxide [4] from burning fossil fuels.

Due to the numerous configurations of the generator-fuel that can be used in DG systems, there is a need to develop control strategies [5] for such diffuse sources, taking into account both the nature of their specific and individual operator preferences. Electricity-producing devices that may be potential sources of distributed generation systems are: reciprocating engines, μ-turbines, fuel cells [6], hydroelectric and wind power plants operating or using geothermal heat (e.g. Organic Rankine Cycle). Each of these devices have different performance characteristics, durability, and operating cost, cost of installation, etc. The possible fuels for such mini-power plants include gases (natural gas, biogas, hydrogen, etc.), liquids (petrol, diesel, bio -liquid fuels, alcohols, etc.) and even solids - using a gasifier - (coal, wood, etc.).

Sources in a distributed system can operate in one of many variants, depending on the individual preferences of the operator. One option is to work for maximum profit - increasing the supply of high-margin power sources, another is to boost the longevity of equipment in order to avoid additional starts and stops, and yet another might be to provide maximum subsistence for a customer's needs (e.g. hospitals). Most operators will probably devise a blend of factors depending on their individual circumstances. An interconnected network of small sources, and their cooperation with the electricity network might add one extra layer of complexity: the operator may cede control of the source to a larger operator who, through control of a large number of similar sources, may have a power comparable to that of a classic large power plant. A network of sources and combined operational control would change power relations.

Current trends in energy and fuels on the market [7] lends additional influence to all those issues. Some operators may cooperate with the distribution network to provide system solutions and situations may arise when the source is disconnected from the network ('island operation'). The selection of individual sources working in a distributed system is a complex issue [8]. Until now, research work on source operation in DG has focused on issues of electrical [9] synchronization with the network, the impact of noise generated, etc. Issues relating to long-term source operation are virtually unrecognized and unexplored. The analysis available applies only to selected elements of the work of DG sources. The influence of the development of distributed generation on power system reliability is presented in [10], indicating the conditions to be met. It was also found that decentralized generation makes it possible to meet the special requirements of users and facilitates their active participation in the market supply and demand game. In [11] sources that can operate as a distributed source were classified: (i) Reciprocating engines; (ii) Gas turbines [12]; (iii) Stirling engines [13]; (iv) Combination systems based on gas turbines [14] and reciprocating engines; (v) Small hydro, wind power; (vi) Photovoltaic systems [15] geothermal power plants [16]; (vii) Fuel cells [17]; and (viii) Systems using: biomass [18] and waste, tides, currents, waves and warm seas. Most available studies almost exclusively concern the issues of electrical and electronic collaboration between the DG source and the power system [11]. The time periods considered there are below 1 second. The proposed variants are closely related to the network source (e.g. through an intermediate network of DC). Issues are also dealt with the same power grid work [19] including the determinants of transmission. The behavior of the power grid of connected sources distributed in emergency situations [20] also on electrical issues was also analyzed.

2. Natural Gas fuelled internal combustion engine – a mathematical model

The analyzed source is a stationary Dachs piston engine made by SenerTec company featuring the parameters are given in table below.

Parameter	Value
Fuel	Methane
Electric power, kW	5.0
Heat output, kW	12.3
Electrical efficiency,%	26
Time between service intervals, h	3,500

Engine efficiency as a function of power was based on actual data from the operation of a Mephisto engine ([21]) after having been normalized and generalized. Changes in the efficiency of the device during off-design operation can be approximated by the following relationship:

$$\eta_{wzgl} = 1{,}2484 \cdot P_{wzgl}^3 - 3{,}0771 \cdot P_{wzgl}^2 + 2{,}8448 \cdot P_{wzgl} \quad (2)$$

where: η_{wzgl} - relative efficiency of the engine, P_{wzg} - relative power. Engine efficiency at the present load is obtained by multiplying relative power by relative electrical efficiency.

Consumption of the chemical energy of fuel can be calculated using the trapezoidal method, in similar fashion to electricity consumption, or by dividing the demand for electric power by the current efficiency of the internal combustion engine.

Fuel consumption can be estimated in paid units of consumption (here: m^3) by knowing the calorific value of the fuel (here: Natural Gas). Whether or not at a given instant of time it pays to produce electricity, or buy it from the network depends on the fuel tariff, electricity tariffs and the time and cost involved in starting and stopping the engine. It is known that the production of electricity by combustion engine is most profitable when heat is produced for heating purposes. However, you may also find that when using a variable-price tariff for electricity (depending on the time of day) production at certain times of day will also be profitable.

When formulating a strategy for use in a particular building (or group of buildings), previous electricity demand must be analyzed carefully. Each day of the week should be considered separately in order to better adapt to the style of life and a seasonal weighting of some description applied. With large data sets covering a number of years, greater weight should be apportioned to newer data.

For reasons of economy it is not recommended for the engine to react too rapidly to load changes (e.g. above 10% P_{max}/1min), because they may be caused by relatively high-power but momentary switching devices such as electric kettles (about 2 kW). Exceptions to the rule may be made if certain sudden increases in demand for electrical power are a predictable, regular occurrence, are noticeable on the average data and are of sufficient length in terms of time.

3. Assumptions of the control strategy for a power source in DG

The control strategy depends on many factors: mainly the daily changes in energy demand that the power source has to cover. It should reflect whether the engine has to work on a base load, top or intermediate configuration. One key element is the choice of objective function from the following options: (i) maximum profit, (ii) maximum lifespan, (iii) meet the needs of their customers. Consideration should also take the weather and fuel prices, electricity, and any funding.

The analysis is based on a sample of three selected cases of changes in demand for electricity: (i) maximum load profile during the week for a library in the UK; (ii) standard load profile G11 tariff group in Poland; (iii) standard load profile G12 tariff group in Poland.

The first case is based on a dissertation by Vasco Guedes Ferreira [22], while the other two - the report [23]. All considered characteristics are scaled to the maximum engine power and then normalized.

Fixed costs include license fees for electricity, which for the tariffs used in this analysis are about \$3/month gross (tariff G12r relating to power companies: “ENERGA-OBRÓT S.A.” and “Energa Operator S.A”). They also include the fixed charge of \$6.34/month gross for gas (transmission & distribution charged by the company “PGNiG”).

Variable costs include primarily the purchase of electricity and the scales of the gas group of “PGNiG” in tariff w-2 for the fuel only (\$0.41/m^3) and tariff E-1A for transmission (\$0.013/m^3).

Revenues include above all the avoided costs of purchasing electricity at a time when producing it is a cheaper way to meet demand.

Revenues include the avoided cost of power failure. For a single-family home (cases 2 and 3) a power outage can cause relatively small financial losses, such as loss of frozen/refrigerated food - about \$100. For case 1 - a large library - it means the absolute impossibility of using the reading rooms (no lighting) and the whole electronic lending system. This situation can result in significant *social* losses (non-material) from the point of view of the library, which affect the behavior of large groups of people such as students. For the latter, it may have a financial dimension, or cause a reduction in academic performance. For a large refrigerated building an outage could quickly turn into a substantial financial loss depending on the season. For hospitals, interruptions in power supplies may even lead to death, which in turn translates into a huge indemnity, and therefore all such facilities are equipped with emergency power sources.

If the stability of power supply is crucial for customer activities, a second electricity connection will be required. The cost of the first connection to a newly built single-family house is about \$3,000. The second connection may prove to be much more expensive investment.

4. The control strategy of IC engine in DG system

Based on several simulations and analyses, the optimum control strategy is determined for the IC engine as power sources in DG. The engine works for maximum profit, which means that only the peak load of the customer is covered by it.

The engine starts up during the morning load peak and works constantly during this time. The next start-up is scheduled for the evening load peak, but because of a rapid load decrease after 19:45 the engine is shut down.

Operation shows that engine efficiency falls below the boundary value at certain times, when it is more profitable to buy electricity from the network. In the periods 13:00-16:00 and 22:00-7:00, electricity taken from the grid is so cheap that the engine will not operate even at the point of its maximum efficiency (excluding emergency cases).

During low demand periods, the costs are only \$0.08/kWh (for all cases taken into consideration), whereas during the morning peak load, the cost reaches \$0.17-0.20/kWh (\$0.20 is the price of electricity taken from the grid).

The case regards the situation of the G11 tariff. In this case, due to the relatively heavy load, the engine works constantly during both peaks and is shut down only during load valleys. For case 2, the electricity costs for the optimal strategy are about \$0.18-0.19/kWh (morning load peak) and \$0.16-0.17/kWh (evening load peak).

The electricity costs for case 3 are \$0.17-0.18/kWh during the morning load peak and \$0.55-0.17/kWh during the evening load peak. During load valleys, the costs are the same as in the previous cases.

To obtain the total profit or losses for each case, it is necessary to compare the results obtained against the results when all power is bought from the grid at constant prices. For this purpose, the tariff provided by the same provider was used – \$0.16/kWh gross. For these assumptions, in case 1 the total profit is about \$0.55/day/kW. The highest profit is obtained for case 3 – \$0.69/day/kW. This means that the demand profile has a material impact on the profit obtained. The other significant factor at play is the choice of an appropriate control strategy.

5. Summary

The control strategy for the IC engine as a DG source of power is presented. From the investigations performed, it was determined that the most appropriate objective function of the strategy is to operate the engine for maximum profit (defined as avoided costs of buying electricity from the grid). Additionally, the profit for operation as an emergency power source was taken into consideration. On average, the IC engine is started up two times per day: during both the morning and evening peak loads.

Profits from operation of the IC engine depend strictly on the load profile and can vary by up to 60%.

Currently, many buildings (e.g. office buildings) have IC engines as emergency power units, but mainly fuelled by liquid fuels (gasoline, oil) – which are more expensive than NG. Those units are not used for power generation. If as expected there is further inflation of electricity prices, power units might be considered for power generation just during peak loads. In those cases, investment (installation) costs are incurred, but in the case of large buildings (with a range of MW), the profits could be quite substantial.

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